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Title:

METHOD OF EVALUATING METABOLISM OF THE EYE

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METHOD OF EVALUATING
METABOLISM OF THE EYE

TECHNICAL FIELD

[0001] The disclosed device generally relates to measuring characteristics within the retina. In particular, the device embodies a non-invasive, single image method and apparatus for measuring metabolic activity within the retina and optic nerve.

BACKGROUND

[0002] FIG. 1 illustrates an exemplary eye 10 including a cornea 20 and a lens 22 to focus and direct light onto a retina 30, which is the light detection and neural processing component of the eye 10. The retina 30 extends from the optic nerve 24, which is composed of retinal nerve fibers, near the posterior pole 26 of the eye 10 to the ora serrata 28 extremity near the anterior segment 32 of the eye 10. The retina 30 contains two types of photoreceptor cells, rods and cones, which generate electrical signals in response to light.

[0003] Failure of any retinal component may result in blindness. For example, total or partial blindness may be caused by a reduction in blood supply to the retina, which in turn, may be the result of diabetic retinopathy or ischemic events such as retinal vein occlusion. Research has shown that other causes of blindness such as cytomegalovirus retinitis, glaucoma, Leber's optic neuropathy, retina detachment, age-related macular degeneration, retinitis pigmentosa, or light induced blindness are commonly associated with the apoptotic, or programmed death of retina cells.

[0004] Apoptosis generally involves the activation of one or more apoptotic signaling pathways by intrinsic or extrinsic stimuli causing the selective degeneration of neurons. The onset of apoptosis has been linked to mitochondrial dysfunction (which is indicative of a change in cellular metabolic activity) characterized by the loss of mitochondrial integrity leading to the release of apoptotic mediators and the activation of enzymes and other pathways leading to cell death. These changes in

mitochondrial integrity result in a gain or a loss of pro- and anti-apoptotic signals and have been linked to the retina disorders that result in 95% of the instances of irreversible blindness. Early detection of mitochondrial dysfunction can allow for diagnosis, treatment, and monitoring of these disorders.

[0005] Current diagnostic techniques used in routine eye examinations typically employ ophthalmoscopes to visually inspect the retina and tonometers to evaluate intraocular pressures. While ophthalmoscopes can be used to diagnose retinal degeneration, they are only effective after substantial damage has already occurred and do not provide any indication of mitochondrial activity. Tonometers indent the eye in order to determine changes in intraocular pressure that may result in glaucoma, retinal ganglion cell death, or ischemia. However, the correlation between intraocular pressure and disease is not robust, as evidenced by patients developing glaucomatous degeneration with low pressures and patients with high pressure remaining disease free. Furthermore, these older methods cannot be correctly interpreted in the presence of biomechanical artifacts such as abnormal corneal thickness due to, for example, natural variations, disease, myopia, or refractive corneal surgery.

[0006] U.S. Patent No. 4,569,354 entitled "Method and Apparatus for Measuring the Natural Retinal Fluorescence" discloses a method and apparatus for determining oxygenation of the retina by measuring the fluorescence of flavoprotein in the retina. According to this patent, a spot of excitation light of a wavelength of about 450 nanometers (nm) is scanned across the retina, in response to which retina auto-fluorescence at a wavelength of about 520nm is detected. In particular, retinal emission light is detected at two wavelengths of about 520nm and 540nm to allow for compensation with respect to absorption and transmission variables in the eye. To compensate for fluorescence of the lens of the eye, the center of the pupil is imaged onto scanning mirrors so

that the scanning beam of excitation light pivots at the center of the eye lens. Because this method and apparatus scans a small area of the retina (i.e. a very limited number of pixels) at a time, the strength of the measured signal is extremely low, resulting in a measured signal having a low signal-to-noise (S/N) ratio and little, if any, accuracy. Further, the small scan area necessitates an extended procedure time to completely scan the retina, which further increases potential for error caused by eye movement due to natural instability of extraocular muscle tone, blood pulsation and light contamination. Because of the inherent inaccuracies of this method and device, it is unable to operate as an accurate diagnosis and monitoring system.

[0007] Accordingly, a device and method for measuring the metabolism of the eye is needed to address the shortcomings of the known diagnostic tools and methods discussed above. Specifically, a device and method for non-invasively measuring the metabolic activity of cells that increases the diagnostic accuracy and speed in detecting retinal disorders is needed.

SUMMARY

[0008] The method and apparatus disclosed herein provides a rapid and non-invasive clinical and experimental tool to measure directly the vitality of a retinal cell based on the auto-fluorescence of excited flavoprotein (FP) within the retinal mitochondria. The disclosed method and apparatus for measuring the retinal auto-fluorescence of a subject retina includes an excitation light source for providing an excitation light at a wavelength of approximately 450nm and an image capture device for recording an ocular auto-fluorescence signal generated in response to the excitation light. The image capture device includes a filter for filtering out undesired wavelengths from the ocular auto-fluorescence signal and includes an image intensifier for increasing the ocular auto-fluorescence signal strength. The method and apparatus may further include a processor that analyzes the ocular auto-fluorescence signal to determine a

contrast change or pattern and can compare serial readings taken at different times or dates. Salient objectives addressed by the device and method disclosed below include: fast procedure time, high accuracy, a direct correlation between retinal metabolic activity and the existence of a retinal disorder, and increased signal-to-noise ratio (S/N).

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a more complete understanding of the disclosed device, reference should be made to the following detailed description and accompanying drawings wherein:

[0010] FIG. 1 illustrates a cross-sectional view of the components of an exemplary eye;

[0011] FIG. 2 illustrates a flowchart embodying the operation of an exemplary retinal testing and evaluation apparatus;

[0012] FIG. 3 illustrates a flowchart embodying the operation of an exemplary calibration routine; and

[0013] FIG. 4 illustrates the functional arrangement of a plurality of components included with an exemplary evaluation apparatus.

DETAILED DESCRIPTION

[0014] Cellular auto-fluorescence may be observed by measuring the emissions of endogenous flavoproteins (FPs) and NAD(P)H molecules. Previous laboratory studies and experiments have shown that cellular metabolic activity is related to the auto-fluorescence of both FP and NAD(P)H molecules. However, NAD(P)H excites and auto-fluoresces in the near ultra-violet range, which promotes cataracts and retinal damage and is, therefore, not suitable for use on living subjects. Therefore, FP auto-fluorescence is being evaluated using, for example, a brief blue excitation light that can be transmitted via the optical structures of the eye without risk of retinal damage. Previous studies have indicated that elevated levels of apoptotic activity correlates with reduced metabolic activity that increases FP auto-fluorescent intensity and reduced metabolic activity. Thus, a method and apparatus that measures the fluorescence

of FP is useful in evaluating retinal metabolic activity in order to aid in the early detection and/or the prevention of blinding disorders.

[0015] FIG. 2 illustrates a flowchart embodying one possible implementation of an exemplary retinal evaluation method 40. At a block 42, a calibration routine 60 (shown in more detail in FIG. 3), can be initiated either manually or upon the occurrence of some predefined condition. For example, the condition for implementing the calibration routine 60 may be based on the non-specific autofluorescence emitted from the eye, a database of autofluorescence images of the same eye examined previously, a database of control eyes imaged previously, a number of cycles or operations that the equipment has performed, the duration of time the equipment has been operating, the calculated mean time before failure (MTBF) of critical components, or any other identified criteria.

[0016] At a block 44, after the calibration routine 60 has been executed, skipped or otherwise completed, the subject to be evaluated can be positioned or aligned relative to the evaluation equipment. It will be understood that the alignment procedure may be accomplished in a variety of ways, such as employing a physical guide used on a desktop ophthalmoscope, fundus camera, or slit-lamp (not shown) to align the subject's head and retina with the equipment, a slit-lamp apparatus, or a retinal fundus camera apparatus. Further, the alignment procedure may be implemented using software by selecting the evaluation area of interest from a presented digital or graphical image. By selecting the area of interest, such as a retinal landmark like the optic disc or vascular patterns, the software may instruct a virtual camera aperture to focus or shift to the identified area of interest or may instruct physical elements within the system to shift and position into the desired or identified location.

[0017] At a block 46, a plurality of microscope objective lenses may be adjusted to a desired focal length. These adjustments may be made

mechanically using, for example, a high precision rack and pinion arrangement to linearly shift the objective lens along the same line defined by the path of light generated by an excitation means, such as a light source. Further, it will be understood that the objective lens may be automatically positioned using a servo or positioning motor system to shift the lens to a predetermined position relative to the physical guide and the subject discussed in conjunction with the block 46. In addition, a range finder or pattern focusing technique (in which a pattern is projected into the optical path and an automatic focusing routine causes the pattern to become the system focal point) could be employed to allow the correct focal length to be automatically determined.

[0018] At a block 48, an excitation means, such as a light source, can be triggered or pulsed to stimulate the flavoproteins (FPs) associated with retinal mitochondria. Excitation may be initiated over a wide range of wavelengths using, for example, a He-Cd or argon-ion laser, and an incandescent or mercury lamp such as an ATTOARC™ variable intensity illuminator. However it is desirable to reduce potential signal noise by limiting the excitation spectrum to a range consistent with the excitation spectrum of FP, approximately 460nm. To this end, an excitation filter such as an OMEGA OPTICAL® Model No. XF1012 (455DF70) excitation filter having a filter range of approximately 420-490nm, may be used. The filtered excitation means stimulates the FP auto-fluorescence without stimulating additional molecules and thereby generating unwanted auto-fluorescence that could act as noise to degrade the overall accuracy of the evaluation technique. It will be understood that the excitation spectrum may be further limited by reducing the ambient light adjacent to the retina 30, which may be accomplished by reducing the testing room lighting, by fitting the subject with goggles, or any other similar method.

[0019] At a block 50, a single image representing the excited FP auto-fluorescence within the retina can be captured. For example, a high-speed charged coupled device (CCD) camera such as a PRINCETON

INSTRUMENTS® PI-MAX ICCD model 512-Gen III camera can be employed to record an image of the auto-fluorescence of the retina. It will be understood that the field of view (FOV) of the CCD camera, with or without the magnification of the objective lens of the block 46, should be established to allow imaging of the retina (or any desired portion thereof) in a single picture.

[0020] One exemplary method of choosing an appropriate FOV to be imaged includes identifying retinal landmarks such as the optic disc or vascular patterns to use as aiming points and then adjusting the FOV to encompass the entire area of interest. Using an appropriate objective lens or lenses, the FP auto-fluorescence may be directed onto a CCD camera. After a set integration time, typically less than one second, the shutter is closed and the image is then downloaded to a computer. The captured digital images can be scanned visually or electronically to find areas of increased brightness, which may be diagnosed as apoptotic regions.

[0021] The CCD camera may further be augmented with a photon intensifier such as the above-identified PRINCETON INSTRUMENTS® image intensifier model Gen-III HQ that includes a photocathode for converting the image into an electrical signal. The electrical signal is multiplied and accelerated into a phosphor screen to produce an amplified image that may then be captured, stored and analyzed.

[0022] At a block 52, the captured amplified image can be analyzed, for example, by a program stored in a computer memory and executed on a processor, to evaluate the metabolic activity within the retina as indicated by the FP signal auto fluorescence. The captured image can be visually analyzed by an observer, trained or otherwise, to determine the presence or absence of patterns, changes or other aberrations of interest. However, as described above, it may also be desirable to automate the analysis procedure using the processor to execute image processing software. A software analysis program may analyze each pixel or element of the image to individually, and in conjunction with the

surrounding pixels, determine local changes in contrast, rates of change in contrast and the existence of patterns. For example, the intensity of a single pixel or a group of pixels may be measured and compared to another adjacent pixel or group of pixels to determine the presence of local changes, patterns, or rates of change etc. which, in turn, can indicate a change in the health and function of the retina 30. The software analysis program may also correlate the captured metabolic image patterns with photography, angiograms, or visual fields corresponding to the same retinal regions. In addition, the program may analyze historical or other stored digital images and compare them to recent or time elapsed images.

[0023] FIG. 3 illustrates the calibration routine 60 that may be implemented at any point during the retinal evaluation method 40. At a block 62, a physical or software controlled calibration procedure can be performed depending upon a maintenance criterion or other selection mechanism. At a block 64, the optics and objective lens can be physically aligned by adjusting the positioning rack and pinion and/or by offsetting or shifting the initial position of a positioning servo or stepper motor. Further, the objective lenses may be rotationally shifted relative to each other to correct for any misalignment that can cause image distortion, blurriness, etc.

[0024] At a block 66, the output strength and alignment of the excitation light source can be evaluated. The excitation light source may include, for example, an internal photodiode that monitors the light intensity and that operates to correct any detected variations in the output strength. Further, the photodiode may simply provide a maintenance signal to indicate when the lamp needs to be replaced. At a block 68, testing hardware, such as a guide for the subject, stand height, chin rest, forehead rest, or other testing hardware can be adjusted or aligned.

[0025] At a block 70, software or electronic calibration may be performed by executing diagnostic routines native to the camera and/or the intensifier. These routines may, for example, compare the stored power levels to detected power levels generated by the CCD camera array in response to a known input. At a block 72, the ambient light present around the retinal evaluation equipment and especially the CCD camera may be measured. One possible manner of determining the ambient light may be to capture and evaluate a known image exposed to known lighting conditions with values stored within the CCD camera or another connected processor, or by using a light meter to detect background ambient light levels at the CCD camera. The difference, if any, between the stored and the evaluated values may then be used to offset the light and/or power levels of the CCD camera. At a block 74, the calibration process 60 may be repeated based on the calculated results or other calibration criteria such as; for example, minimum determined CCD intensity and/or excitation light source intensity. If the calibration procedure is not repeated, the method may return to the retinal evaluation routine 40 as indicated.

[0026] It will be understood that the exemplary retinal evaluation method 40 described above provides a non-invasive evaluation method that is clinically and experimentally useful because, among other things, the methodology is inexpensive, quick, and painless while requiring a minimum of patient effort. As discussed above, the endogenous fluorochrome flavoprotein (FP) provides an indication of the retinal metabolic activity within retinal cells and can be monitored in a reliable, non-invasive fashion.

[0027] Preliminary studies of the exemplary evaluation method 40 illustrated in FIGS. 1 and 2 included performing *in vitro* studies on isolated retinal cells and *ex vivo* studies on two isolated human retinas. The *in vitro* experiments compared the auto-fluorescence excitation spectra of purified FP component and an unlabeled human leukocytes using a 530nm

emission wavelength. The excitation properties can be evaluated using a microfluorometry apparatus to perform excitation spectroscopy associated with the 530nm excitation emission. The *in vitro* experiments confirmed that the emissions detected at the 530nm, based on the correlation between the two samples, are likely to have originated with the auto-fluorescence of the flavoproteins (FPs) of interest.

[0028] The *ex vivo* experiments were performed on human retinal tissue having a high content of retinal pigment epithelial (RPE) cells including oxidized, fluorescent melanin and dark granules. The physical experiment employed the OMEGA OPTICAL® Model No. XF1012 (455DF70) excitation filter in conjunction with a 495nm long-pass dichroic reflector. It will be understood that filtered excitation means may be directed and delivered to the subject/patient using a fiber optic harness and system. Emission spectroscopy of the excited retinal tissue showed a peak at 530nm, which has been identified as matching the known FP auto-fluorescence. These emission results were confirmed by examining the retinal emission spectra in the presence of a metabolic inhibitor, which caused an increase in FP auto-fluorescence, and in the presence of cyanide, which caused a reduction in FP auto-fluorescence. The results of these experiments confirmed that emission intensity of FPs relate inversely with the level of mitochondrial activity (e.g., an increase in metabolic activity results in a decrease in FP auto-fluorescence).

[0029] FIG. 4 illustrates an exemplary apparatus for performing retinal evaluations generally indicated by the numeral 80. Generally, the evaluation apparatus 80 includes a still camera, a charged coupled device (CCD) camera 82, and an excitation light source 84 arranged to capture a single image representing the FP auto-fluorescence present within the subject retina 30. If a CCD camera 82 is used, it may be, for example, a cooled CCD camera that may include a Peltier cooler to reduce the temperature of the detector and thereby decrease thermally generated electronic noise or dark current noise. As previously discussed, the retina

30 can be stimulated by the excitation light source 84 and the resulting FP auto-fluorescence can be recorded by the still camera or the CCD camera 82. It will be understood that the CCD camera 82 can be selected to have FOV optimized to capture the single image or in the case of a still camera, photographic image. Upon analysis, the image captured by the CCD camera 82 allows a direct and non-invasive procedure for determining the metabolic activity or health of the subject retina 30.

[0030] In operation, the excitation light source 84, which may be a mercury lamp such as an ATTOARC™ mercury lamp having a bright mercury line near 440nm, or a laser of similar wave length, cooperates with a focusing lens 86 to direct the emitted excitation light 84a to an excitation filter 88. The excitation filter 88 may be, for example, the OMEGA OPTICAL® excitation filter described above and may be selected to prevent light of wavelengths beyond the range of approximately 400-500nm from being transmitted to the subject retina 30. The filtered light 88a may then be directed to a dichroic reflector 90, such as the 495nm long-pass dichroic reflector discussed above, for redirection towards the subject retina 30.

[0031] The redirected filtered light 88b may then pass through an optics stage 92 which may include a microscope objective 94 and a contact lens 96 or a fundus or slit-lamp camera apparatus. The microscope objective 94 and the contact lens 96 may act to focus, align and magnify the redirected filtered light 88a onto a desired area of the subject retina 30. It will be understood that under some test conditions, an applanation means such as a flat, optically clear lens or plane may be used to flatten or deform the cornea 20 to a desired shape to thereby allow better or more accurate imaging. Alternatively, an appropriate contact lens for fundus viewing may be employed.

[0032] The focused redirected light 88c illuminates the retina thereby causing auto-fluorescence of the associated flavoproteins (FPs). The generated FP auto-fluorescence 82a may be directed away from the

subject retina 30 and through the components of the optics stage 92, and the dichroic reflector 90 to an emission filter 98 such as, for example, an OMEGA OPTICAL® Model No. XF3003 (520DF40). The emission filter 98 may be selected to prevent wavelengths that do not correspond to FP auto-fluorescence wavelength, (e.g., wavelengths of or around 530nm) from passing through its structure. The filtered FP auto-fluorescence 82b may then pass through a focusing lens 100 which focuses FP auto-fluorescence 82c on the still camera or CCD camera 82. At this point the filtered FP auto-fluorescence 82b may be displayed on a video display unit 104 such as a LCD or cathode ray tube for visual evaluation, or may be communicated to a personal computer 106 for analysis, storage or other desired image processing.

[0033] The CCD camera 82 may further include and cooperate with an image intensifier 102 to magnify the brightness of the focused FP auto-fluorescence 82c to facilitate analysis of the captured image. The image intensifier 102 will likely be selected such that the gain, which is the ratio between the signal captured by the detector of the CCD camera 82 and the corresponding output signal, represents an increase of 100 to 1000 times the original image intensity. The image can be acquired, for example, by using a high-speed PRINCETON ST-133 interface and a STANFORD RESEARCH SYSTEMS® DG-535 delay gate generator with speeds ranging from 5nsec to several minutes. The delay gate generator cooperates with the CCD camera 82 and the image intensifier 102 to synchronize and control the operation of these components. It will be understood that this captured image represents only the focused FP auto-fluorescence 82c in an intensified form, the unwanted auto-fluorescence information or noise having been minimized by the operation of the excitation filter 86 and the emission filter 98. In this manner, the resulting single image captured by CCD camera 82 has a high S/N ratio and provides a clear and detailed image representing the FP auto-fluorescence 82a-82c.

[0034] The components of the retinal evaluation apparatus 80 described herein may be used in a stand alone fashion, wherein alignment is accomplished via manual clamping and securing of the individual components. However, the imaging, excitation and optical components of the retinal evaluation apparatus 80 may be integrated into any known desktop or handheld ophthalmoscope, slit-lamp, or fundus camera, to allow easy upgrade to the testing equipment described herein. Specifically, the CCD camera 82, the excitation light source 84, the optics stage 92, and the associated components may each be equipped with an adaptor (not shown) designed to allow each of the individual components of the retinal evaluation apparatus 80 to be mated with the ophthalmoscopes and other devices discussed above. In this case, the standard ophthalmoscope, fundus, or slit-lamp light may be replaced with the excitation means 84 affixed to the ophthalmoscope frame using a bracket or adaptor and the light output by the excitation means 84 maybe filtered to produce the desired excitation light 84a. An image detection device may be attached to the frames of the devices and aligned opposite the retina 30 to detect a single image representing the FP auto-fluorescence generated in response to the excitation light 84a. In this manner, existing devices can be retrofitted to allow known diagnostic equipment to be used to excite and evaluate retinal auto-fluorescence.

[0035] Although certain retinal evaluation systems and methods have been described herein in accordance with the teachings of the present disclosure, the scope and coverage of this patent is not limited thereto. On the contrary, this patent is intended to cover all embodiments of the teachings of the disclosure that fairly fall within the scope of the permissible equivalents.